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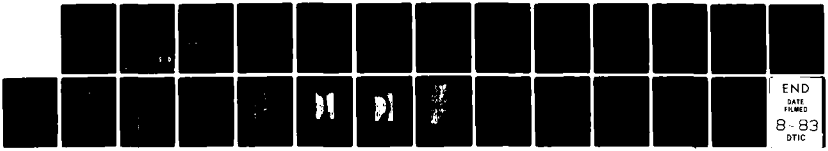

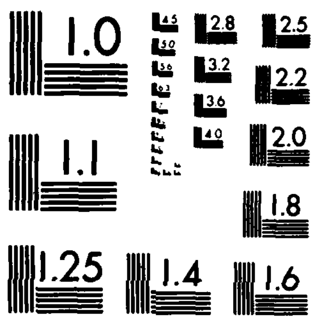


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# EXPERIMENTAL SPINAL TRAUMA STUDIES IN THE HUMAN AND MONKEY CADAVER

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## Abstract

Compression studies were conducted on the ligamentous thoracolumbar spines of fresh human male cadavers. For comparison, forces were applied to the posterior upper thoracic region of intact seated cadavers. Since this type of injury routinely involves ligament failure and vertebral body wedge compression fractures, studies were conducted on single vertebral bodies and isolated ligaments. Similar studies were conducted in isolated monkey ligaments. The intact and ligamentous thoracolumbar spines failed predominately in the region of the thoracolumbar junction at forces from 1113-5110 N. For both the human and monkey cadavers, the anterior longitudinal ligament was the strongest. The human ligaments were 2-5 times stronger than those of the monkey.

## Introduction

Spinal cord injuries are often observed following vertebral body dislocation and ligament failure with attendant bone or disc destruction. Many studies have been done to retrospectively describe the force vectors associated with these injuries. However, few quantitative studies have been performed on the total isolated or intact spinal preparation (1-6). In contrast, considerable emphasis has been directed to studies of functional elements and their components (7-11). To elaborate the mechanisms and forces associated with spinal injuries, studies have been conducted in the cadaveric human and monkey spine.

Previous studies have evaluated flexion, extension and axial tension and compression applied to the cervical spine (6, 12-15). This study is focused upon the thoracolumbar spine. The human cadaveric isolated thoracolumbar spine was vertically loaded in compression to determine the region of fracture and the strength of the bone and ligament components involved in injury. For comparison, compression forces were applied to the posterior upper thoracic region of the intact seated cadaver. Because ligament failure is routinely observed in spinal trauma, the strength of the individual ligaments of the isolated human cadaveric spine was measured. Since the sub human primate is often used in experimental spinal injury studies, similar measurements were made in macaque monkeys.

## Methods: Ligamentous thoracolumbar spine studies

Studies were conducted in 14 fresh human male ligamentous thoracolumbar spines. All specimens were determined to be within normal limits from the medical history, and x-ray examination prior to the test. The tissues were maintained at $2^{o}$ C until studied within 1-3 days of death. Lactated Ringer's solution was used to keep the preparation moist before and during testing,

which was performed in a high humidity environment. Injury was determined by x-ray and gross dissection following the study. The method of fixation has been previously described (6). Briefly, Steinman pins were driven into the upper and lower vertebral bodies and posterior elements and molded into 15 cm diameter aluminum cylinders with methylmethacrylate (Fig. 1). Twelve of the specimens were mounted between T2-T4 and L5-sacrum. The cervical elements were included in the other two. The columns were preflexed and vertical forces were applied with an MTS Systems Corporation electrohydaulic system at rates of 1-120 cm/sec. Forces and deflections were recorded on a model 1858 Honeywell Visicorder and a Norland model 4001 digital oscilloscope. Angles at failure were measured radiologically at the level of injury. Failure was defined as the point at which the force decreased with continued deflection.

For comparison, 32 isolated single thoracic and lumbar vertebral segments from 10 human cadavers were compressed with vertical loads applied to the endplate surfaces of thoracolumbar elements. The individual vertebral bodies were placed between solid cylinders with a diameter larger than the vertebral body and compressed at 0.1 cm/sec to half of the initial height (Fig. 2).

Methods: Intact cadaver studies

Comparative studies were done in 4 human intact male cadavers. The subjects were preflexed and seated on a 0.5 x 1 m horizontal steel platform mounted on the actuator frame immediately under the MTS piston. Forces were applied at 1 cm/sec. with a 15 X 15 cm flat plate at the T1, T2 region of the cadaver. The preparations were fixed at the pelvis with belt restraints, and lateral stabilizing structures were used (Fig. 3). The posterior elements of the spine in the thoracic and lumbar area were surgically exposed. X-rays were taken prior to, during and following the study.

## Methods: Isolated spinal ligament studies

The isolated ligamentous spines of twelve fresh human male cadavers ranging in age from 34 to 78 were studied. For comparison, two 8-10 kg male rhesus (*Macaca mulatta*) and four 8-10 kg male stumptail (*Macaca arctoides*) monkeys were also isolated. All specimens were determined to be within normal limits from the medical history and x-ray examinations conducted prior to the test. The isolated ligamentous spines were carefully removed to avoid damage to the ligaments. All tissues were kept at 2 degrees centigrade until studied within 1 to 3 days of death. Liberal amounts of Ringers solution were used to keep the preparation moist during the test. A high humidity environment was maintained during the test. In seven of the human preparations segments extended from the first thoracic element through the sacrum. All ribs were removed from these preparations. The spinal segments were divided at T9 or T10 to leave the thoracolumbar junction intact. At each vertebral level all ligaments except the one under study was sectioned with a dissecting microscope. The vertebral bodies above and below the ligament under study were fixed in a frame with five Steinman pins (Figure 4). The apparatus was aligned to pull each ligament in direct axial tension at rates of 1 to 100 centimeters per second using an MTS electrohydraulic apparatus. The anterior and posterior longitudinal ligaments, both joint capsules, interspinous ligaments, ligamentum flavum and intact discs were studied.

A Norland 4001 digital processing oscilloscope was used to record the data from a Kistler load washer. Data from the linear differential transformer of the MTS device and the potentiometer were recorded on a Honeywell model 1858 visicorder and the Norland digital oscilloscope.

Representative tissues were sliced on an LKB cryomicrotome (16). The tissues were frozen using liquid nitrogen and maintained at -70° C. The heavy

duty sledge cryomicrotome was used to trim sections from the specimen. Photographs of the remaining surface were obtained at 1 mm intervals with a camera coupled to the moving knife holder. A cloth soaked in ethylene glycol was used to eliminate ice crystals from the surface which produced anatomic images with bright natural colors.

Results: Ligamentous thoracolumbar spines

Eleven of the 14 isolated ligamentous spines demonstrated wedge fractures at vertebral levels from T9 to L1 (Fig. 5,6)(Table 1). An average force of 2055.6 Newtons (N) was required (Table 2). When the spines which included the cervical elements are eliminated, the average failure load was 2285.2 N. The angles between the vertebral bodies at the level of failure ranged from 23 to 40 degrees with an average of 29.2 degrees. Disruption of the posterior ligamentous complex was routinely observed.

The forces required for fracture increased for lower spinal levels. For the 6 subjects which failed at T2-T9, the average force was 1223.5 N while those which failed at T10-L1 required 2680.2 N.

In three subjects, the sections above the below the fracture level were remounted and tested. With 6-8 vertebral segments, the forces required for failure ranged from 3600-5000 N.

The ultimate forces for the single vertebral bodies in compression ranged from 1500-7400 N. The stiffness, taken as the initial slope of the force-deflection curve, ranged from 3550 to 19700 N/cm with a mean of 9520 N/cm (Table 3).

Results: Intact cadavers

The four intact human cadavers demonstrated wedge compression fractures of the vertebral bodies at forces from 1110 N to 2750 N. The angles between the vertebral bodies at the level of failure ranged from 28 to 50 degrees.

Three of the specimens failed between T10 and L2 while the fourth was fractured at T7. The posterior ligaments were avulsed in all of the cadavers (Fig. 7). A load report was heard when the ligaments failured. The anterior surface of the vertebral body was reduced approximately 25 percent in height.

Results: Isolated spinal ligaments

The average strength of the anterior longitudinal ligament at thoracic and lumbar levels in the male human cadaver ranged from 180 to 500 N, with the highest values obtained at lumbar levels (Fig. 8). The anterior longitudinal ligament of the monkey exhibited a similar variation with vertebral level with the strength ranging from 27 to 300 N in the thoracic and lumbar spine (Table 4).

The posterior longitudinal ligament was strongest at mid thoracic levels. The average strength ranged from 45 to 160 N. The range in the monkey was 10 to 90 N with the largest values at the thoraco-lumbar junction.

The joint capsule was left intact bilaterally for these studies. The average maximum load for failure ranged from 90 N at mid thoracic levels to 380 N at lumbar levels. The corresponding values for the monkey are 45-200 N.

The ligamentum flavum was strongest at low thoracic levels (270 N) with the lowest values obtained in mid lumbar levels (90 N). No appreciable difference was observed between the rhesus and stumptail monkey ligament strength. For the monkey thoracic and lumbar spine, the ligamentum flavum failed at 80-150 N with little variation with vertebral level.

The interspinous ligament demonstrated a range of 45-200 N with the highest values in the mid thoracic spine. A similar variation with vertebral level was observed for the monkey with a range of 10-120 N.

## Discussion

King et al. (2) show that the spinal column can be protected by the facets which tend to unload the vertebral bodies in the erect position or during hyperextension. A block placed at L1 to produce hyperextension increases the fracture levels at the vertebral body from 10 to 18 $G_{+z}$. Fracture levels for older cadavers in $G_{+z}$ impacts were 17.75 $\pm$ 5.5 G (hyperextended), 10.4 $\pm$ 3.79 G (erect), and 9.0 $\pm$ 2.00 G (flexed) (1,17). For ejection, the vertebral fractures in 78 aviators were 75.7% thoracic, 22.3% lumbar and sacral, and 2.8% at the cervical level (18). In additional studies Ewing determined the structural properties of the vertebral column of the human cadaver (1). Ruff conducted stress analysis of the human spinal column (4). He determined static breaking loads for the T8 vertebrae of 5884 N and 9800 N for L5 in fresh cadaver specimens.

The thoracolumbar injuries which were produced in the intact and isolated ligamentous spine in this study are similar to those observed clinically. Most of the failures were at the thoracolumbar junction and the posterior ligaments were routinely disrupted. In contrast Roaf did not observe ligamentous failures in functional units with vertebral body fractures (19). The different findings are probably due to studies with functional units versus newly complete spines. The forces required for failure in the intact preparations did not differ significantly from those in the ligamentous spines. However, as is true for other experimental injury studies, the effects of normal muscle tone cannot be evaluated.

The compressive strength values for the vertebral bodies measured in this study were similar to those reported by Kazarian (8). The strengths of the ligaments were in reasonable agreement with those reported by Tkaczuk (20) for human lumbar longitudinal ligaments and by Hyler (21) and Little (22) for

the monkey. Shorter spinal columns and short segments of the spinal column required greater forces for failure as predicted by column theory. However, the failure loads were significantly higher than the critical forces reported by Lucas (23) for the spinal column. Further, increasing loads were observed with increasing flexion, up to the point of failure. A free body analysis of the intact cadaver studies suggests that for an average failure load of approximately 1800N ($F_A$), applied to the posterior upper thoracic region 5167 N ($F_L$) of tension would be developed in the posterior ligaments, and approximately 7412N ($F_V$) of compression would be applied to the vertebral body (10). These calculations assume an upper torso weight of 445 N ($F_w$), perpendicular distance from posterior ligaments of 5 cm ($L_L$) to the center of the T12 body, 7.5 cm for the perpendicular distance to the torso center of gravity ($L_W$). Perpendicular distance from the vertebral body point of rotation to the applied force is 12.5 ($L_A$) (Fig. 9).

With the frequency of flexion injuries to the thoracolumbar spine (3,9), the ligamentous cadaveric spine model presents a useful method for the evaluation of biomechanical parameters associated with these injuries. The comparison of the monkey and human ligaments suggests that human ligaments are 2 to 5 times stronger than those of the monkey.

## Summary

Ligamentous thoracolumbar spines from 14 fresh human male cadavers failed at loads of 555-5110 N, with a mean of 2055.6 N. Four intact cadavers failed at forces of 1110-2750 N, with a mean of 1787.5 N. The wedge compression fractures were predominately in the region of the thoracolumbar junction. Posterior ligament failure was routinely observed. The longitudinal ligament was strongest in both the human and monkey cadavers.

The posterior longitudinal ligament was usually the weakest. The human ligaments were 2 to 5 times stronger than those of the monkey.

ACKNOWLEDGEMENT

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Table 1: Forces and angle of failure in the fresh male human isolated spine and in the intact cadaver. (N = 0.2248 pounds).

| Specimen | Age | Failure | Failure load | Failure angle degrees |
|---|---|---|---|---|
| S-10 (T3-L5) | 76 | L1 compression | 1730 N | 40° |
| S-11 (T3-L5) | 55 | T11 compression | 1113 N | -- |
| S-12 (T2-sacrum) | 57 | T9 compression | 967 N | -- |
| S-13 (T3-L5) | 84 | T7 compression | 2220 N | -- |
| S-16 (T2-sacrum) | 80 | T11 compression | 1720 N | 32° |
| S-17 (T2-sacrum) | 65 | T9 compression | 799 N | -- |
| S-18 (T4-T5) | 41 | T12 compression | 4444 N | |
| S-27 (C2-L5) | 56 | T7 compression | 555 N | |
| S-28 (C2-L5) | 64 | T2 compression | 800 N | |
| S-29 (T2-L5) | 71 | T12-L1 compression | 1330 N | 4[illegible] |
| S-31 (T3-sacrum) | 58 | T10 compression | 5105 N | 40° |
| S-32 (T3-sacrum) | 63 | T9 compression | 2000 N | 40° |
| S-33 (T3-sacrum) | 76 | T11 compression | 1775 N | 36° |
| S-38 (T3-sacrum) | 48 | T11 rotation | 4220 N | 23° |
| S-34 (intact) | 63 | T11 compression | 1555 N | 30° |
| S-39 (intact) | 56 | L2 compression | 2750 N | 28° |
| S-42 (intact) | 43 | T10-T11 compression | 1110 N | 30° |
| S-43 (intact) | 61 | T7 compression | 1735 N | 50° |

Table 2: Forces for failure of the fresh male human cadaveric thoracolumbar spine in flexion. n = number of specimens.

| | n | range | mean | standard deviation |
|---|---|---|---|---|
| All ligamentous spines | 14 | 555-5110 N | 2055.6 N | 1468.2 N |
| Failures at T2-T9 | 6 | 555-2220 N | 1223.5 N | 702.6 N |
| Failures at T10-L1 | 8 | 1113-5110 N | 2680.2 N | 1617.3 N |
| Intact cadavers | 4 | 1110-2750 N | 1787.5 N | 693.4 N |

Table 3: Dimensions and ultimate compresive forces for thoracic and lumbar vertebral bodies of the fresh male human cadavers.

| | n | average surface area ($cm^2$) | average initial height (cm) | range | mean |
|---|---|---|---|---|---|
| Upper Thoracic (T1-T6) | 10 | 7.2 | 1.85 | 1557-3470 N | 2638 N |
| Lower Thoracic (T7-T12) | 13 | 10.2 | 2.10 | 1557-5560 N | 3278 N |
| Lumbar | 9 | 16.3 | 2.60 | 1957-7384 N | 4972 N |

Table 4: Comparison of forces for disruption of single ligaments in the fresh human male and fresh rhesus and stumptail male monkey cadaveric spine.

| | Human Cadaver Range | Monkey Cadaver Range |
|---|---|---|
| <u>Ligament</u> | | |
| Anterior longitudinal | 180-500 N | 27-300 N |
| Posterior longitudinal | 45-160 N | 10-90 N |
| Joint capsules | 90-380 N | 45-200 N |
| Ligamentum flavum | 90-270 N | 80-150 N |
| Interspinous ligament | 45-200 N | 10-120 N |

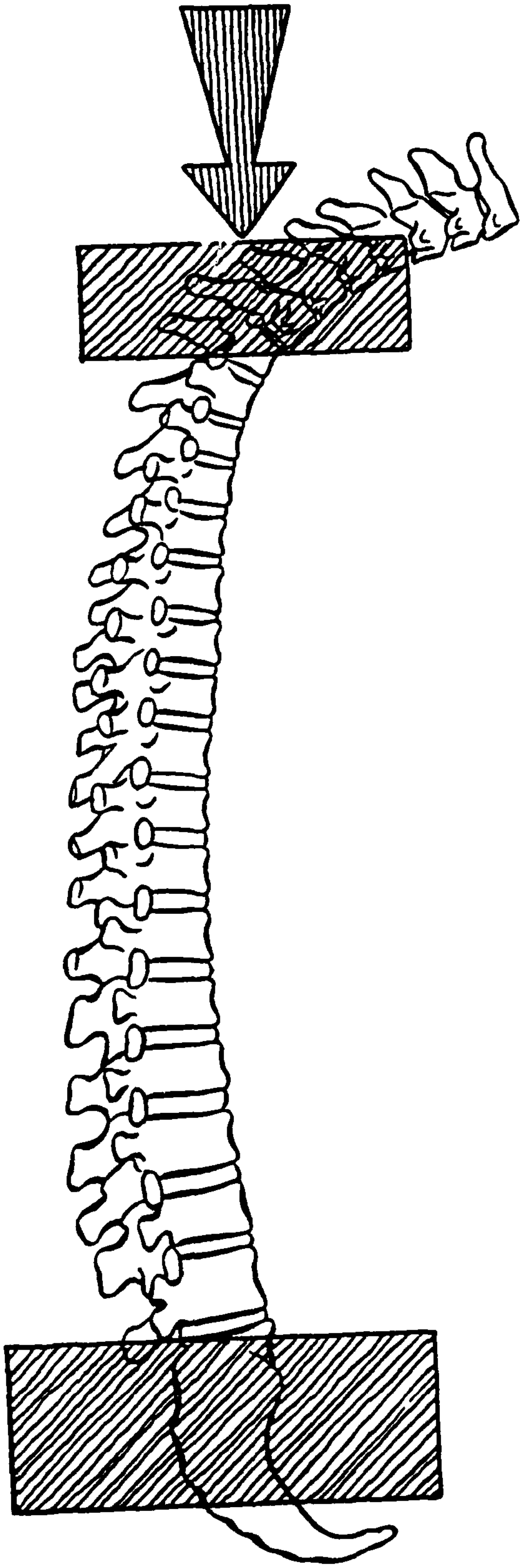

Figure 1: Schematic representation of the fixation for the ligamentous thoracolumbar spine studies. Steinman pins were driven into the upper and lower vertebral bodies and molded into aluminum cylinders with methylmethacrylate. The spines were preflexed and vertical force was applied.

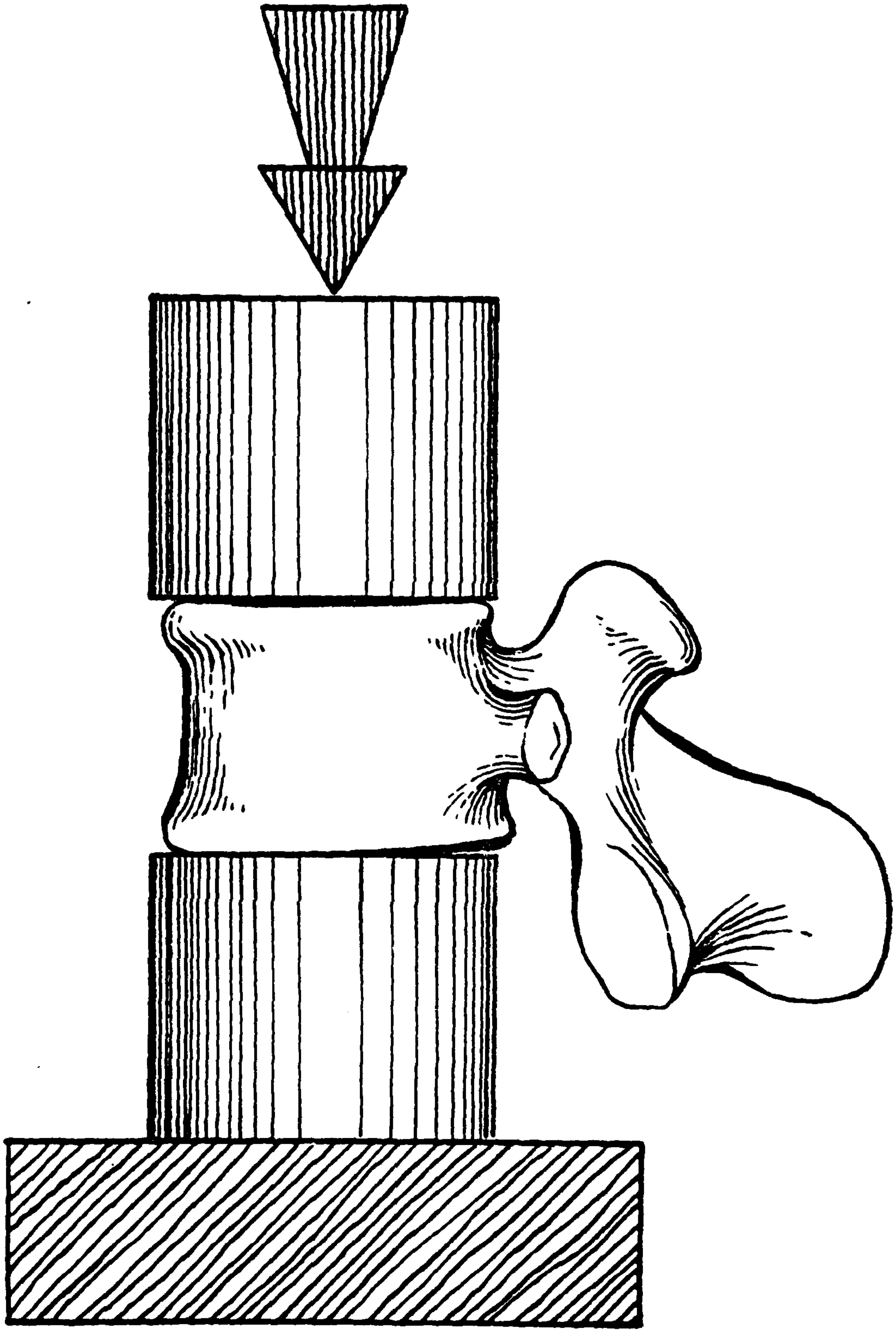

Figure 2: Schematic representation of the method utilized for compression of the vertebral bodies. The individual bodies were placed between cylinders with diameter larger than the vertebral body.

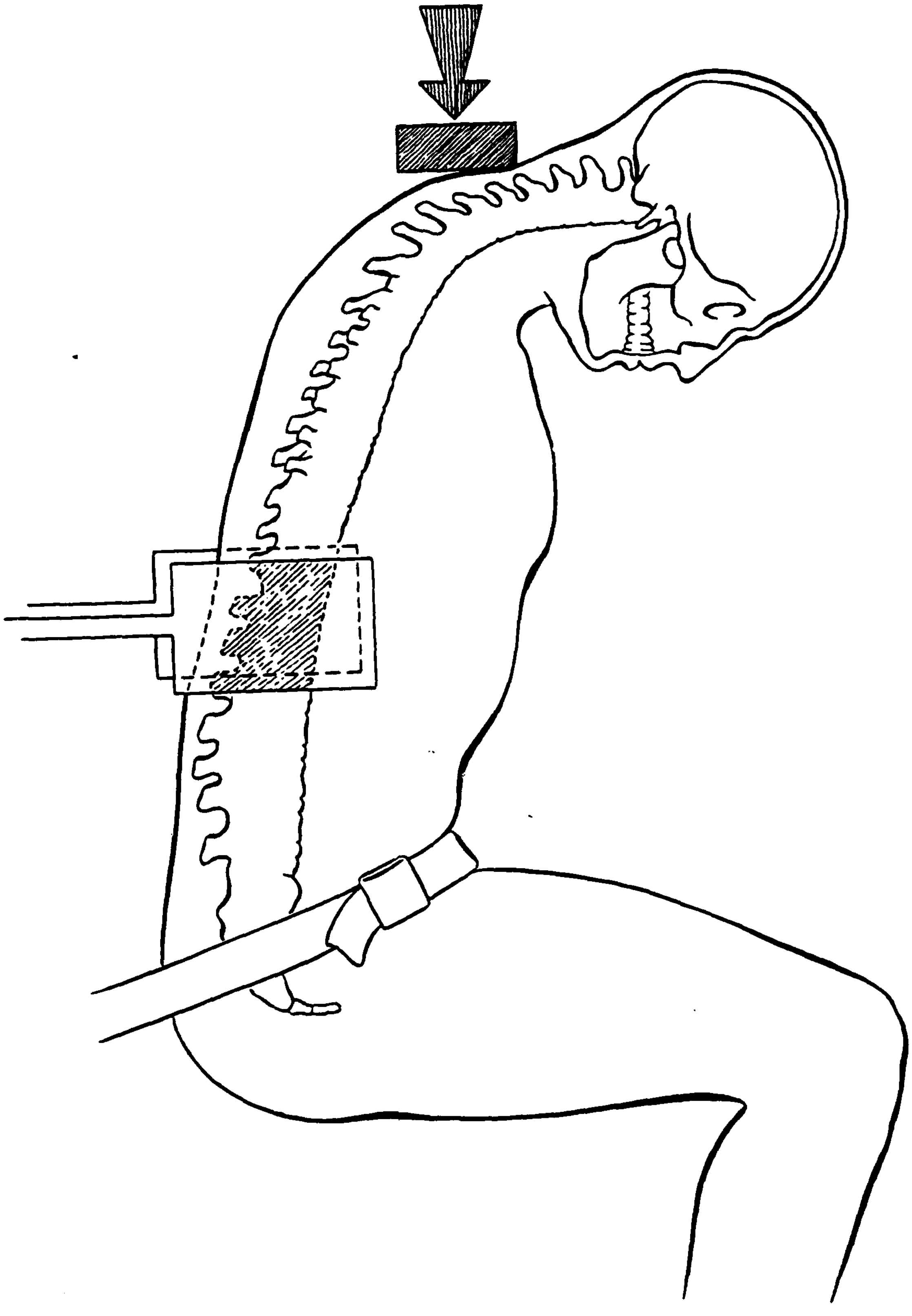

Figure 3: Schematic representation of the fixation for the intact cadaver studies. The subjects were preflexed and seated on a 0,5X1m steel platform mounted on the activator frame under the MTS piston. The specimens were fixed at the pelvis with belts and lateral stabilizing structures were used. Forces were applied at T1, T2 with a 15 X 15 cm flat plate.

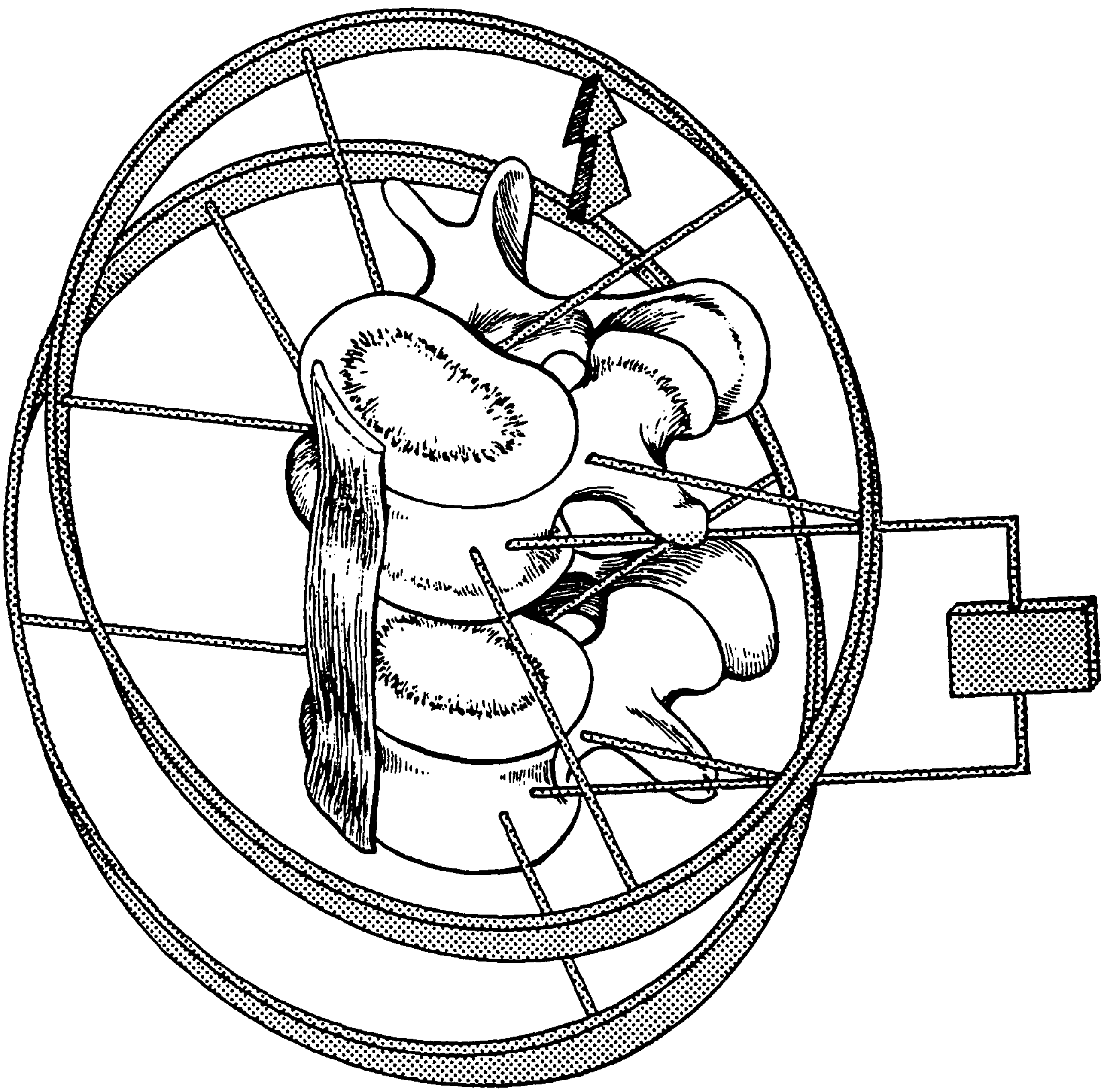

Figure 4: Schematic representation of method of fixation for individual ligament tests. All of the ligaments except the one under study were sectioned. The vertebral bodies above and below the ligament were fixed in a frame with five Steinman pins. The apparatus was aligned with the piston of the MTS system, and tensile forces applied.

Figure 5: S-16. This is an anterior to posterior view with the column in a slight lateral angulation. The arrow points to the T10, T11 endplate failure.

Figure 6: This is a lateral view with the column in a flexed position. The arrow points to the T10, T11 endplate failure with a compression fracture to the body of T11.

Figure 7: X-ray of 539 demonstrates minimal anterior wedging, with posterior element and posterior vertebral body disruption at L2. The angle at failure is 28° by the Loff Method. The load at failure was 2750 N.

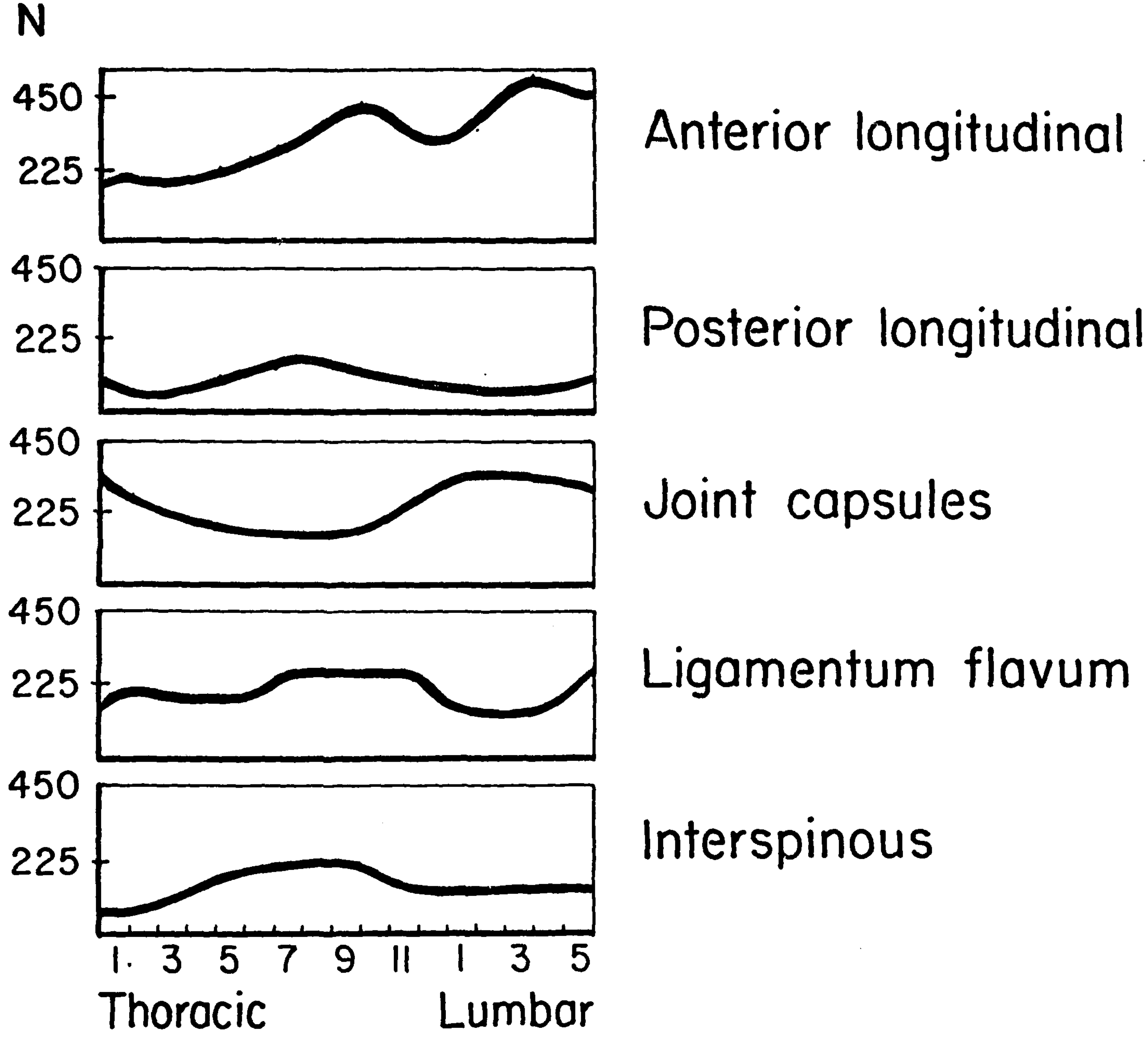


Figure 8: Breaking loads versus vertebral body level for the anterior longitudinal (A), posterior longitudinal (B), joint capsules (C), ligamentum flavum (D), and interspinous ligament. Studies were conducted in fresh male human cadavers.

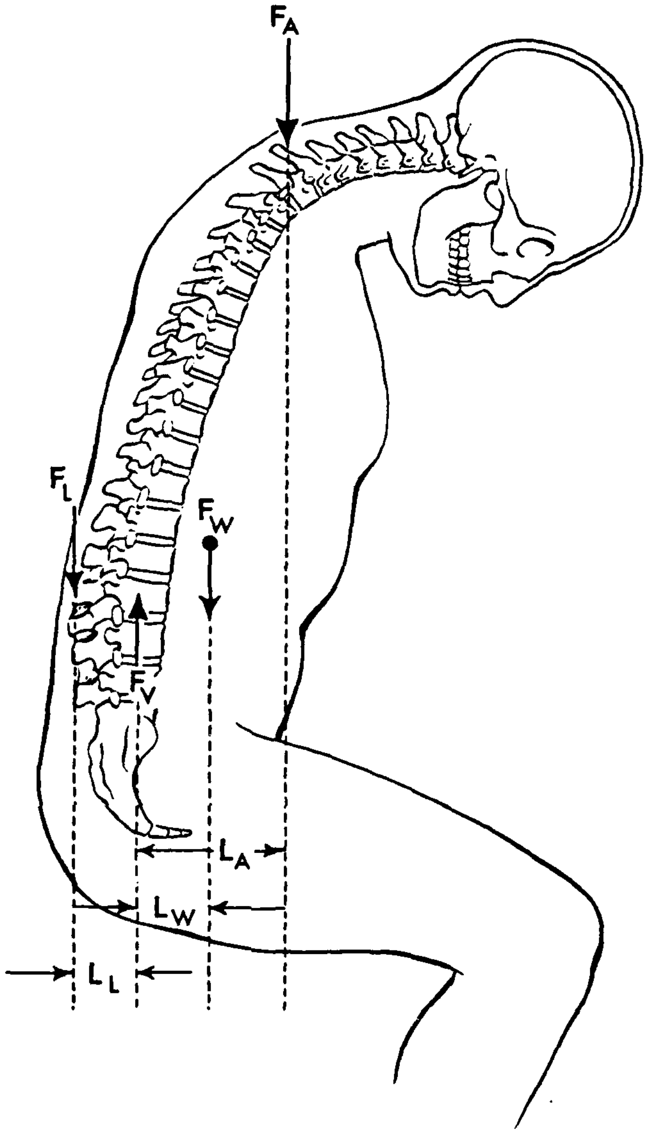


Figure 9: Schematic illustration of relevant forces and distances for externally applied force ($F_A$) to produce thoracolumbar injury, $F_L$ = force in posterior ligaments, $F_W$ = weight of upper body acting at center of gravity, $F_V$ = force on vertebral body, $L_L$, $L_W$, $L_A$ are corresponding distances from point of rotation about vertebral body to line of action of force.

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